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Effects of different management approaches on soil carbon dynamics in Moso bamboo forest ecosystems

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ABSTRACT

Moso bamboo (*Phyllostachys pubescens*) is a very important forest resource in subtropical China, and it has excellent carbon sequestration potential, and can play an important role in mitigating climate change. The international community has gradually recognized the benefits of Reducing Emissions from Deforestation and Forest Degradation (REDD+) forest carbon sequestration mechanisms, and the areas available for the development of forest carbon sinks have greatly expanded. Therefore, in this study, we use a two-factor randomized complete block design in which fertilization rate and harvesting intensity were selected to investigate the changes in soil organic carbon (SOC) concentration and carbon (C) storage from 2010 to 2016. With 3^k orthogonal method, a factorial analysis with 3 levels of fertilization (high (1800), medium (900) and low (0 kg ha^{-1} year^{-1})) and 3 levels of harvesting intensity (high (100%), medium (50%) and low (0%) cutting of the bamboo of 4–5 years old) has been taken. Our results show that fertilization, harvesting, and the fertilization × harvesting interaction had significant effects on SOC concentration changes, but not on C storage after six years of management. Only the interaction between high fertilization and high intensity harvesting, which we called the intensive management model, caused a decrease of 4.48 Mg C ha^{-1} in the 0–50 cm soil layer C storage. The interaction between no fertilization and low intensity harvesting, which we called the traditional management model, increased soil carbon C by 7.90 Mg C ha^{-1}. The optimized management model of high fertilization and medium intensity harvesting increased soil C the most; by 59.94 Mg C ha^{-1}, which is 2.36 times larger than that of the intensive management model, and 1.86 times larger than that of the traditional management model. The results clearly reveal that the soil carbon pools in Moso bamboo forest have a great carbon sequestration potential under the optimized management model.

1. Introduction

Bamboo, with 1250–1500 species in 75–107 genera (Ohrnberger, 1999; Scurlock et al., 2000; Zhu, 2001), is an important component of many forest ecosystems in subtropical and tropical regions (Song et al., 2011). Bamboo is distributed across approximately 31.5 million ha of land, accounting for approximately 0.8% of the world's total forest area in 2010 (FAO, 2010; Song et al., 2011). China has approximately 4.84–5.71 million ha of bamboo forests (Chen et al., 2009; Li and Kobayashi, 2004; FAO, 2010; Song et al., 2011), mostly in the south, and 63% of these are Moso bamboo (*Phyllostachys pubescens*) forests (Wang et al., 2008). Moso bamboo forests play an important role in atmospheric C sequestration and soil erosion control in degraded areas (Zhou et al., 2011).

Moso bamboo can sequester great quantities of carbon as their very high growth rate results in a corresponding increase in CO_2 uptake through photosynthesis (Zhou et al., 2009; Du et al., 2010; Düking et al., 2011; Lobovikov et al., 2012) and decelerate climate change (Lobovikov et al., 2009; INBAR, 2010; Nath et al., 2015). For example, mean above ground carbon uptake of a 29-year-old Taiwan red cypress (*Chamaecyparis formosensis*) and a 33-year-old Japanese cedar (*Cryptomeria japonica*) was reported as 2.83 and 4.44 Mg C ha^{-1} year^{-1}, respectively, which was much lower than the 8.13 Mg C ha^{-1} year^{-1} reported for Moso bamboo (Nath et al., 2015). The results of comparing aboveground carbon sequestration between Moso bamboo and Chinese fir forests showed that Moso bamboo (8.13 Mg ha^{-1} year^{-1}) had a

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higher carbon sequestration rate than that of Chinese fir (3.35 Mg ha^{-1} $year^{-1}$) (Yen and Lee, 2011). In addition, Moso bamboo may be used for commercial purposes. The edible shoots of Moso bamboo are valued for their taste, and the timber of Moso bamboo has been widely used for furniture manufacturing, housing construction, outdoor terrace building, and fuel (bamboo charcoal) (Restrepo et al., 2016).

For these reasons, intensive management practices have been widely applied in the past few decades to increase the growth of Moso bamboo, and thus achieve higher economic returns (Wang et al., 2008; Liu et al., 2011; Qin et al., 2017). Such management practices include inorganic fertilizer application, cutting, tillage, and regular removal of understory vegetation. Previous studies indicate that the long-term application of these practices may cause negative ecological consequences such as soil erosion and nutrient leaching (Shinohara and Otsuki, 2015), increases in soil CO_2 emission (Liu et al., 2011), acceleration of soil organic C mineralization (Zhou et al., 2006; Jiang et al., 2009), and decreasing soil organic C storage (Li et al., 2013).

The benefits from Reducing Emissions from Deforestation and Forest Degradation (REDD+) forest carbon sequestration are increasingly recognized, and the area allocated for the development of forest carbon sinks has been greatly expanded. What means that forest management has an important potential role in REDD projects for increasing forest soil carbon. This has created opportunities and challenges for China's bamboo management in recent years (Wang et al., 2013; Zhang et al., 2014; Nath et al., 2015). Therefore, previous intensive management methods in Moso bamboo forests, which aimed to maximize economic benefits, might be transformed to methods to improve carbon sequestration, in order to achieve a new balance between economics and ecology. This study evaluated the effects of different management approaches on soil carbon dynamics, and explored the relationships between management intensity and soil C storage changes in Moso bamboo forests in subtropical China. In addition, our results provide theoretical and technological knowledge for carbon sink management in Moso bamboo forests.

2. Materials and methods

2.1. Study site

The study site is located in Linan county (E119°45′, N30°10′) Zhejiang Province (Fig. 1), China. This site had an undulating topography, with elevation ranging from 90 to 200 m a.s.l. The climate is a subtropical monsoon climate, with an average precipitation of 1350–1500 mm per year, and a mean annual temperature of 15.9 °C, with the highest temperature in July, and the lowest in January. It has 1774 h of sunshine annually, and a frost-free period of 236 d. The forest coverage rate was up to 65%. The main tree species was Moso bamboo. The soils in the experimental site were derived from siltstone, and were classified as a slightly acidic red soil in the Chinese system of soil classification (State Soil Survey Service of China, 1998), equivalent to the Ferralsols in the FAO soil classification system (WRB, 2006). Soil thickness was 50 cm.

Prior to the start of our experiment, the old bamboo (> 6 years) was harvested every two years, while the young bamboo (< 6 years) was left standing. The stocking density of the bamboo forests was 3236 stem ha^{-1}, with a mean diameter at breast height of 9.1 cm. The understory had few shrubs, but many weeds. The permanent sample plots were established in 2010, no tillage was applied, and the understory vegetation was retained.

2.2. Experimental design

A two-factor randomized complete block design was employed, in which fertilization rate and harvesting intensity were selected. The fertilization and harvesting were applied as follow:

(i) Fertilization rate: large amount of fertilizer (1800 kg ha^{-1} $year^{-1}$, applied twice a year, referred to hereafter as 'high fertilization'), medium amount of fertilizer (900 kg ha^{-1} $year^{-1}$, applied twice a year, referred to hereafter as 'medium fertilization'), and no fertilizer applied. Bamboo shoot special fertilizer (N 13%, P 3%, K 2%, amino-acid ≥8%, organic matter ≥15%, and humic acid ≥10%) was applied by furrow beginning in January 2010.

(ii) Harvesting intensity: high intensity harvesting (all bamboo of 4–5 years old was cut), medium intensity harvesting (half of the bamboo of 4–5 years old was cut), and low intensity harvesting (all bamboo of 4–5 years old was left uncut). Under this management, all bamboo of 1–3 years old was left standing, and all bamboo older than 5 years was cut. Selective cutting occurred every two years.

With the 3^k orthogonal method, The field experiment consisted of nine management treatments (high fertilization and high intensity harvesting [F_1H_1], high fertilization and medium intensity harvesting

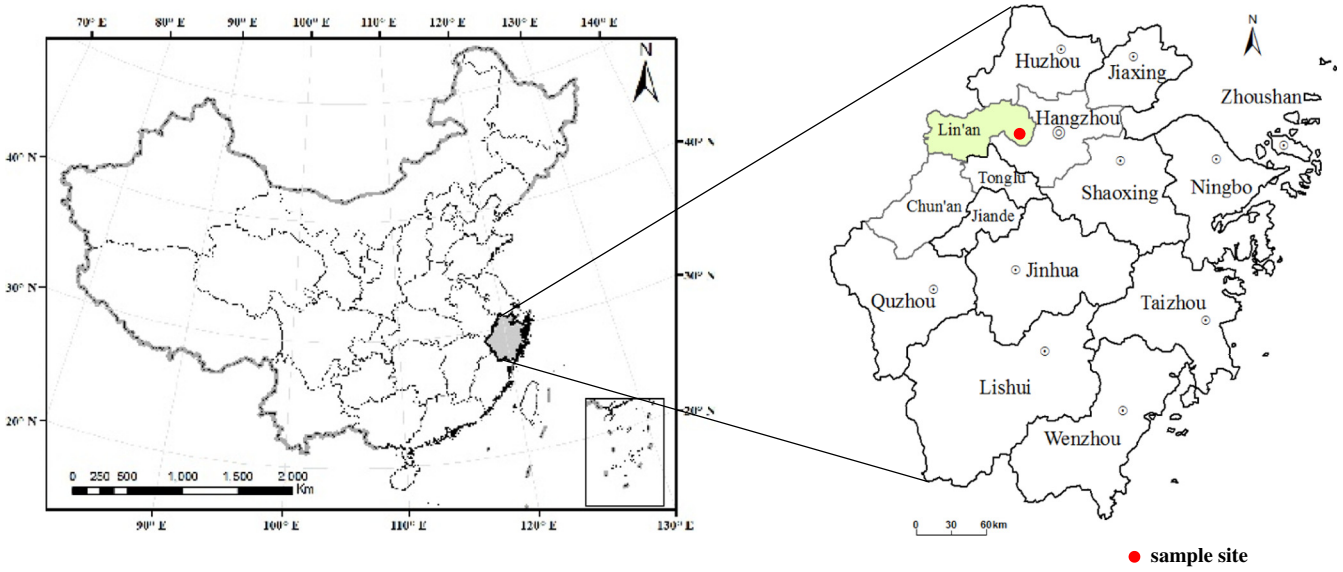

Fig. 1. Location of the sample site.

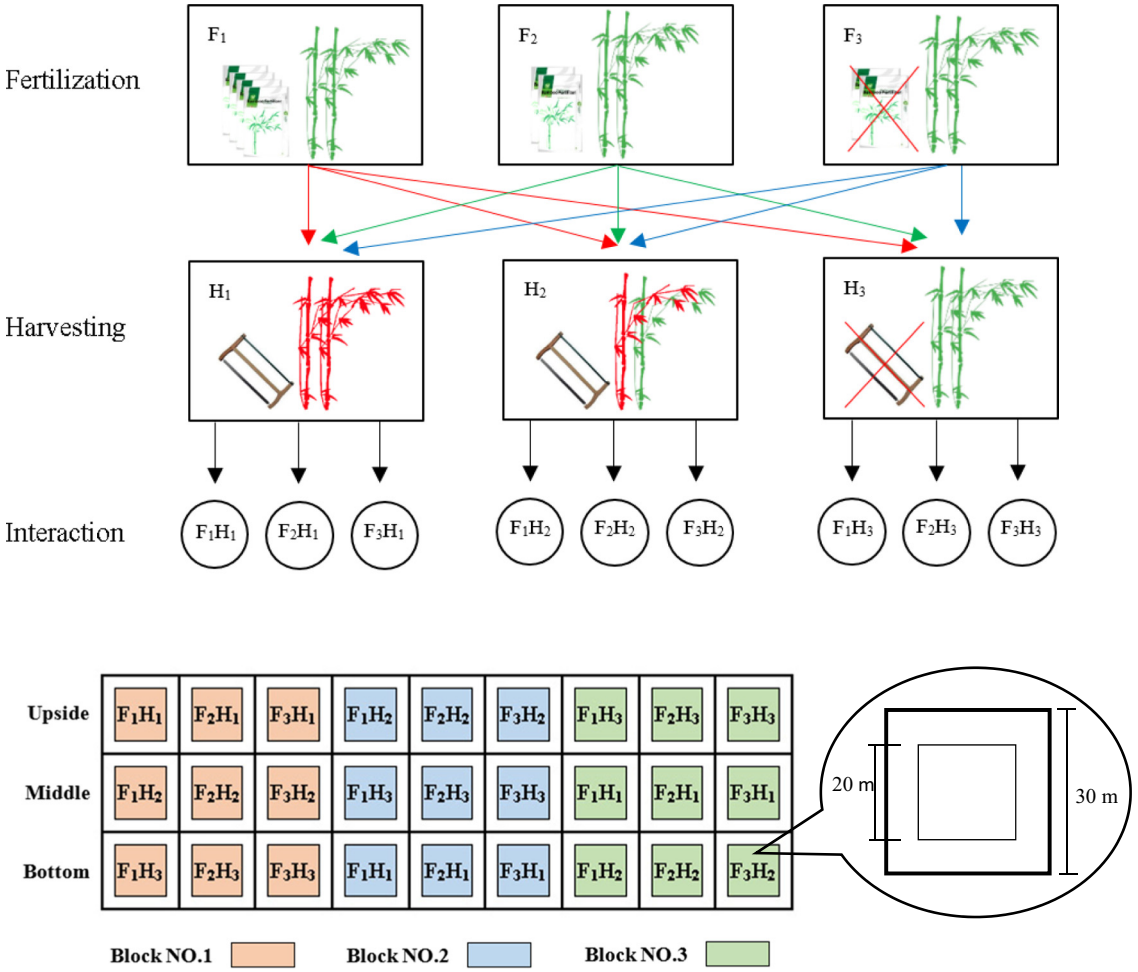

Fig. 2. 3^k orthogonal method result and the randomized complete block design. The object of selective cutting is 4–5 year old bamboo. F_1, F_2 and F_3 refer to amounts of fertilizer applied (high, medium, and none respectively). H_1, H_2, H_3 refer to intensity of bamboo harvesting (high, medium, and low respectively). The white area indicates a buffer, 30 m refers to the length of the border around the plots. 20 m refers to the length of the border around the data collecting area. See Materials and Methods for details.

$[F_1H_2]$, high fertilization and low intensity harvesting $[F_1H_3]$, medium fertilization and high intensity harvesting $[F_2H_1]$, medium fertilization and medium intensity harvesting $[F_2H_2]$, medium fertilization and low intensity harvesting $[F_2H_3]$, no fertilization and high intensity harvesting $[F_3H_1]$, no fertilization and medium intensity harvesting $[F_3H_2]$, no fertilization and low intensity harvesting $[F_3H_3]$) (Fig. 2), applied to experimental plots (30 × 30 m) with three replicates for each treatment (resulting in 27 independent plots). In our trial, we had three blocks. Each block had three sample plots on a slope, with plots on the upper side, middle, and bottom, respectively (Fig. 2). Every treatment had sample plots on the different slope position. Treatment F_1H_1 is referred to as the intensive management model, and treatment F_3H_3 is referred to as the traditional management model.

Due to the growth traits of Moso bamboo, each plot included a 5 m wide buffer (Fig. 2) to reduce the interference from the bamboo rhizome spread in the adjacent plots. Experimental treatments were applied to the whole plot, although data was collected only from the central area (20 × 20 m) of every plot.

2.3. Soil sampling and soil physicochemical analysis

Soil samples were collected from the 27 plots in June 2010, 2013, and 2016, respectively. Within each plot, soil samples were taken at 0 to 10, 10 to 30, and 30 to 50 cm depths from five randomly selected points. The five soil cores from the same layers were placed in a clean plastic bucket and mixed thoroughly to form a composite sample, and then brought to the laboratory. After removing all visible roots and plant fragments (> 2 mm diameter), soil cores were air-dried at room temperature, and ground to pass through a 2 mm or 0.25 mm sieve for chemical analysis.

Briefly, soil pH was determined using a soil-to-water ratio of 1:2 with a pH meter (PB-10, Sartorius, Germany). Soil moisture was measured by oven-drying a sub-sample of the soil at 105 °C for 24 h. After determining the soil moisture of the bulk density samples, we calculated the bulk density based on the volume and total oven-dry weight of the soil within each soil core (Lu, 1999). The soil organic carbon (SOC) concentration was determined by wet digestion with 133 mmol L^{-1} $K_2Cr_2O_7$ and concentrated H_2SO_4 at 170–180 °C (Walkley and Black, 1934). Soil organic carbon (SOC) stocks were calculated using the following equation:

$$CS_{soil}\,(\text{Mg C ha}^{-1}) = \sum_{i=1}^{n} BD_i \times Cconc_i \times D_i \times 0.1$$

where CS_{soil} is the C stock of soil (Mg C ha^{-1}), BD_i is the soil bulk density in i layer (Mg m^{-3}), $Cconc_i$ is the SOC concentration in i layer (g kg^{-1}), D_i is the thickness of i soil layer (cm), and i is the soil layer number.

2.4. Statistical analyses

The data presented in this paper are the averages of three replicates. A three-way analysis of variance (ANOVA) was conducted to test factors (fertilization, harvesting, and soil layer), and their interaction effects on SOC concentration, and we also used a two-way analysis of variance (ANOVA) to test factors (fertilization and harvesting) and their interaction effects on C storage. When the ANOVA analysis indicated a significant treatment effect, the Tukey test was used to separate the means. An alpha level of 0.05 for significance was used in all statistical analyses. The statistical analyses were performed using SPSS version 19.0 (SPSS Inc.). The diagrams were made using GraphPad Prism version 6.

3. Results

3.1. Dynamic changes of SOC concentrations and C storage

There were clearly distinct trends in soil C pools over the time sequence. Compared with 2010, both 2013 and 2016 had a significant increase in average SOC concentrations and soil C storage in the 0–50 cm soil layer ($P < 0.01$), while there was no significant difference between 2013 and 2016 (Fig. 3a and b). The results show that SOC concentration increased from 2010 to 2013, and then decreased from 2013 to 2016, ranging from 9.7 to 13.3% (Fig. 3a), whereas soil C storage from 2010 to 2016 increased significantly by 53.09 and 82.95 Mg C ha^{-1} (Fig. 3b). After three years of management, there were significant differences in SOC concentrations in different soil layers. The SOC concentration in the 0–10 cm soil layer was greater than that in the 10–30 cm and 30–50 cm layers in each year (Fig. 3c). With the increase in soil depth, it was clear that both SOC concentrations and C storage reached an equilibrium after a significant increase under three years of management (Fig. 3d).

3.2. Effects of different management measures on changes in SOC concentrations

A three-way ANOVA showed that there were significant effects of fertilization ($P = 0.001$), harvesting ($P = 0.016$) and the fertilization × harvesting interaction ($P = 0.039$) on SOC concentration changes from 2010 to 2016, and the effect of fertilization was stronger than that of harvesting and their interaction (Table 1). There was no significant effect of fertilization, harvesting, and soil layer on SOC concentration changes from 2010 to 2013, and no significant interaction was observed (Table 1). This indicates that, after six years of management, the significant effects of fertilization and harvesting were stronger than that of their interaction, and the interaction effect was becoming weaker.

The boxplots of SOC concentration change values ($n = 27$) under different fertilization rates, harvesting intensities, and soil layers are shown in Fig. 4. The SOC concentration changes in 2010–2013 and 2010–2016 both exhibited a similar pattern, with an initial increase, and a subsequent decrease with the decrease of fertilization rate, with mean values ranging from 2.1 to 5.9%, and 0.003 to 5.2%, respectively. The multiple comparison results indicated that there was no significant effect of high fertilization, medium fertilization, and no fertilization on SOC concentration changes from 2010 to 2013 (Fig. 4a), while there were significant differences between medium fertilization and no fertilization ($P < 0.05$), and high fertilization and no fertilization ($P < 0.05$) on SOC concentration changes from 2010 to 2016 (Fig. 4b).

Unlike fertilization, the SOC concentration changes in 2010–2013 increased with the decrease of harvesting intensity, with mean values ranging from 1.3 to 5.5%, while the SOC concentration changes in 2010–2016 displayed an initial significant increase, and a subsequent decrease with the decrease of harvesting intensity, with mean values ranging from 1.5 to 5.3%. The multiple comparison results indicated that there were no significant differences between any two types of harvesting intensity on SOC concentration changes from 2010 to 2013 (Fig. 4c), while there were significant differences between high intensity harvesting and medium intensity harvesting on SOC concentration changes from 2010 to 2016 ($P < 0.05$) (Fig. 4d).

Compared with fertilization, soil layer exhibited a similar pattern, with an initial increase and a subsequent decrease with increasing soil depth, with mean values ranging from 2.3 to 4.7%, and 1.2 to 4.3%, respectively. The multiple comparisons results indicated that there were no significant effects of soil layer I, soil layer II, and soil layer III on SOC concentration changes both from 2010 to 2013, and from 2010 to 2016 (Fig. 4e, f).

3.3. Effects of different management treatments on soil C storage changes

A two-way ANOVA showed that there was no significant effect of fertilization and harvesting on C storage changes both in 2010–2013 and 2010–2016, and no significant interaction was observed.

The boxplots of changes in C storage values ($n = 9$) under different fertilization rates and harvesting intensities are shown in Fig. 5. The C storage changes in 2010–2013 and 2010–2016 both exhibited a similar pattern, with an initial increase and a subsequent decrease with the decrease of fertilization rate, with mean values ranging from 13.48 to 38.85%, and 12.05 to 42.79 Mg C ha^{-1}, respectively. The multiple comparison results indicated that there was no significant effect of high fertilization, medium fertilization, and no fertilization on C storage changes both in 2010–2013 and 2010–2016 (Fig. 5a, b). Unlike fertilization, the C storage changes in 2010–2013 increased with the decrease of harvesting intensity, with mean values ranging from 9.30 to 33.97 Mg C ha^{-1}, while the C storage changes in 2010–2016 displayed an initial increase and a subsequent decrease with the decrease of harvesting intensity, with mean values ranging from 19.76 to 37.84 Mg C ha^{-1}. The multiple comparison results indicated that there were also no significant differences between any two types of harvesting intensity on C storage changes both in 2010–2013 and 2010–2016 (Fig. 5c, d).

The changes in soil C storage in the 0–50 cm soil depth in Moso bamboo forests from 2010 to 2013 reached a maximum (52.8 Mg C ha^{-1}) under treatment F_2H_3, and a minimum (-10.1 Mg C ha^{-1}) under treatment F_1H_1 (Fig. 6). From 2010 to 2016, C storage in the 0–50 cm soil depth increased significantly under treatment F_1H_2, F_1H_3 and F_2H_1, by 59.9 Mg C ha^{-1}, 48.7 Mg C ha^{-1} and 49.9 Mg C ha^{-1}, respectively (Fig. 6). Only the change value under treatment F_1H_1 was negative (-4.5 Mg C ha^{-1}) (Fig. 6).

4. Discussion

4.1. Effects of fertilization, harvesting, and interactions on SOC concentration and storage

Significant effects of fertilization, harvesting, and the fertilization × harvesting interaction were found on SOC concentration changes from 2010 to 2016 (Table 1). For fertilization, this is in agreement with the results of He et al. (2018), who found that long-term fertilization significantly increased soil organic carbon in three wheat-maize cropping sites across central and south China. Similar results were obtained by Ghosh et al. (2018), who noted that total soil organic carbon concentrations increased significantly after 44 years of wheat based cropping. For harvesting, a simulation study by Taylor et al. (2008) indicated that selective cutting, i.e. continuous cover forestry, would increase SOC concentrations. In Norway, Nilsen and Strand (2008) found that the difference in SOC concentrations between a selectively harvested stand and an even-aged and thinned stand established after clear-cutting in the early 1930s was 21 Mg C ha^{-1}, with the selectively cut stand having the higher SOC concentration. Little was previously known about the interaction between

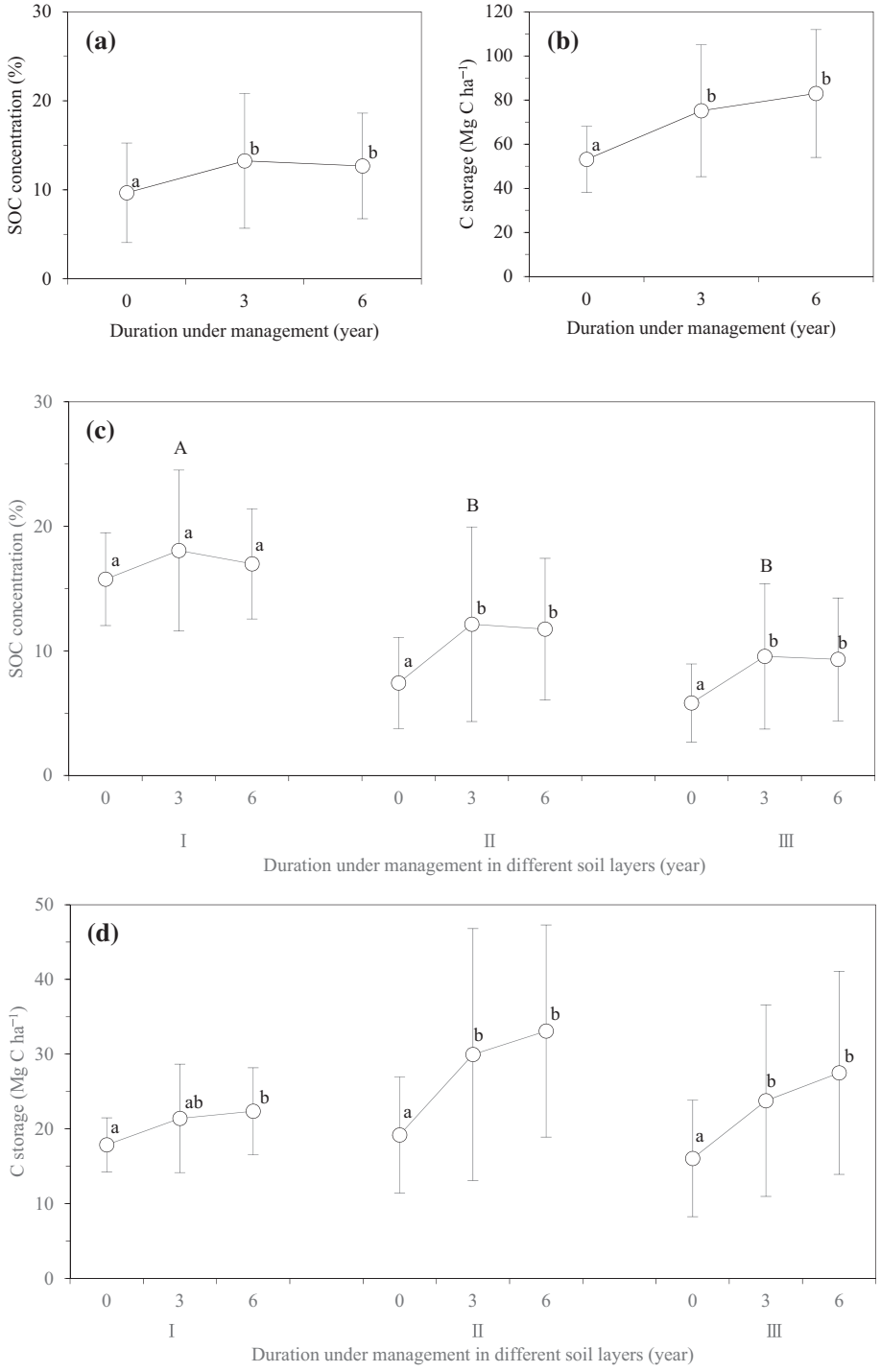

Fig. 3. The dynamic changes of SOC concentrations and C storage in different soil layers with increasing duration under management. I: 0–10 cm soil depth; II: 10–30 cm soil depth; III: 30–50 cm soil depth. (a) and (b): Different lowercase letters above the circles indicate significant differences among different years for the SOC concentrations and C storage at $P < 0.05$; (c) and (d): Different lowercase letters above the circles indicate significant differences among different years for the SOC concentrations and C storage at $P < 0.05$, different capital letters indicate significant differences among different soil layers for the SOC concentrations at $P < 0.05$.

fertilization × harvesting in Moso bamboo forest. What caused the significant effects of this interaction on SOC concentration changes might be that Moso bamboo forest was disturbed frequently, interactions between different fertilization rate and harvesting intensity have a great influence on SOC concentrations.

The SOC concentration saw the biggest increase in 2010–2013 and 2010–2016 at medium levels of fertilization (Fig. 4a, b). This is probably due to the fact that adding fertilizer increases both microbial decomposition of SOC and inputs of C to soil via crops, but it increases inputs more than it increases losses, leading to increased SOC (Gong et al., 2012). Zhang et al. (2015) also reported that a moderate rate of fertilization, considered an effective practice, could increase the soil C stocks in chestnut plantations. The SOC concentration at low intensity harvesting increased the most in the first three years of management, while it occurred at medium intensity harvesting in six years of management (Fig. 4c, d). Similar results were obtained by Wollum and

Table 1
Summary of the three-way ANOVA on the comparison of SOC concentration changes in 2010–2013 and 2010–2016.

Effect	2010–2013			2010–2016		
	df	F value	*P* value	df	F value	*P* value
Fertilization (F)	2	2.180	0.123	2	8.034	**0.001**
Harvesting (H)	2	2.419	0.099	2	4.491	**0.016**
Soil layer (SL)	2	0.781	0.463	2	2.846	0.067
F × H	4	0.701	0.595	4	2.711	**0.039**
F × SL	4	0.569	0.686	4	0.972	0.431
H × SL	4	0.182	0.947	4	0.373	0.827
F × H × SL	8	1.027	0.427	8	1.437	0.203

Note: *P* values < 0.05 are indicated in bold.

Schubert (1975), Carey et al. (1982), and Vesterdal et al. (1995), who noted that forest floor C stocks decreased with increasing thinning intensity in field studies in New Zealand, Denmark, and the USA. The explanations for these results might be similar to those for the results for thinning interventions in Piene and Cleve (1978) and Aussenac (1987). Selective cutting changes the microclimate, and decomposition of forest floor C is temporarily stimulated because soils become warmer and possibly wetter due to reduced evapotranspiration (Jandl et al., 2007). These influences depend on harvesting intensity. Therefore, the SOC concentration at low intensity harvesting increased the most in the early stage of management, while it occurred at moderate-intensity harvesting with increasing duration under management.

However, as for soil C storage changes, there was no significant effects of fertilization, harvesting, and the fertilization × harvesting interaction in 2010–2013, nor in 2010–2016. A possible reason for this could be that our bamboo shoot special fertilizer was an organic complex fertilizer, which may increase SOC concentration while simultaneously decreasing soil bulk density. Similar results were reported by Celik et al. (2010), who noted that compost application resulted in the lowest bulk densities occurring at 0–15 and 15–30 cm soil depths, whereas the highest bulk density values were obtained with mineral fertilizer application. Furthermore, soil C storage was determined by SOC concentration, soil bulk density, and soil thickness. As such, when fertilization, harvesting and the fertilization × harvesting interaction had significant effects on SOC concentration changes, the effects of these on C storage changes might not be significant.

4.2. The dynamic changes of soil C pools under different management

SOC concentrations significantly decreased with soil depth under different management treatments in Moso bamboo forests (Fig. 3c). This is in agreement with the results of Zhao et al. (2017), who indicated that the SOC content decreased with soil depth, especially in grasslands and forestlands. Similar results were obtained by Song et al. (2016), who noted that SOC concentrations decreased with increasing soil depth in both oak (*Quercus* spp.) forests and black locust (*Robinia pseudoacacia*) plantations. Wang et al. (2012a) also found that SOC concentrations under all land uses decreased sharply with increasing depth of the soil profile in the hilly Loess Plateau. This result was consistent with the observations of a previous study (Wang et al., 2012b), in which there existed a clearly stratified distribution and downward trend of SOC contents with increasing soil depth as a whole, due to the effects of plant allocation above- and underground (Jobbagy and Jackson, 2000).

Effects of different management treatments on average SOC concentration and C storage reached an equilibrium level after a significant increase with increasing duration under management (Fig. 3a, b). This result was inconsistent with Li et al. (2014), who reported that soil C stock in intensively managed Chinese chestnut (*Castanea mollissima Blume*) plantations was being depleted. In addition, Li et al. (2010) showed that soil total organic C did not significantly increase during the initial period of intensive management (from one to five years), but dramatically increased after five years. Due to its biological characteristics and growth habits, Moso bamboo is one of the fastest-growing plants, and it has an excellent carbon fixing capability. It can be selectively harvested every two years and sustainably used (Zhou et al., 2009, 2011).There were periods of adjustment and stability during the management, and the period of adjustment (which was the equivalent of the rotation period) in this study was six years, because the age structure of the sample plots was composed of bamboo that was 1–5 years old. Possible mechanisms for the significant increase of average SOC concentration and C storage from 2010 to 2013 include (1) the application of organic inorganic compound fertilizer, (2) no tillage was applied, and (3) understory vegetation was retained. Previous studies have shown that applying inorganic compound fertilizer may increase SOC concentrations in soil (for examples see Angers and N'dayegamiye, 1991, Gerzabeck et al., 2001, and Liang et al., 2012). These results were also consistent with Zhang et al. (2015), who concluded that a combination of a moderate rate of fertilization should be adopted to increase soil C sequestration, maintain soil fertility, and sustainably develop chestnut plantations. In addition, no tillage and retained understory vegetation reduced the loss of SOC, similar to the results reported by Heiskanen et al. (2007) and Ruiz-Colmenero et al. (2013), who found that intensive management practices such as tillage and understory vegetation removal induce the loss of SOC, especially labile C forms.

4.3. Response of soil C storage to interactions and carbon sequestration potential

Only interaction between high fertilization and high intensity harvesting caused the decrease of 0–50 cm soil C storage from 2010 to 2016 (Fig. 6). Li et al. (2010) and Li et al. (2013) both similarly found that long-term intensive forest management practices, including annual inorganic fertilizer application, tillage, and removal of understory vegetation, markedly changed the quality and quantity of SOC in Moso bamboo forests, including reducing the SOC stock. A possible explanation for these results would be the fact that high intensity management decreased the soil organic C stability, and increased the risk of releasing CO_2 through soil organic C mineralization.

After six years of management, the interaction effect between high fertilization and medium intensity harvesting increased the C storage the most in the 0–50 cm soil layer, by 59.94 Mg C ha^{-1} (Fig. 6), which indicates that the soil has a great potential for carbon sequestration. Dangal et al. (2017) found that there was no distinct difference between an intensive management model and a traditional management model in soil carbon stock of pine plantations. The soil carbon stock was 78.65 Mg C ha^{-1} under the intensive management model, and 75.96 Mg C ha^{-1} under the traditional management model in pine plantations (Table 2). However, in Moso bamboo forest, Li et al. (2013) reported that the soil carbon stock under the traditional management model was 30.74 Mg C ha^{-1} larger than that under the intensive management model (Table 2). As for this study, under the optimized management model, the soil carbon stock was 112.15 Mg C ha^{-1}, which is 2.36 times larger than under the intensive management model, and 1.86 times larger than under the traditional management model. Therefore, this management model showed excellent carbon sequestration potential in soil, and benefited from the REDD + forest carbon sequestration mechanisms.

5. Conclusions

The relationships between different management approaches and soil carbon dynamics located in a Moso bamboo forest ecosystem of Zhejiang Province (southeastern China) were studied.

The results highlighted that, after six years of management,

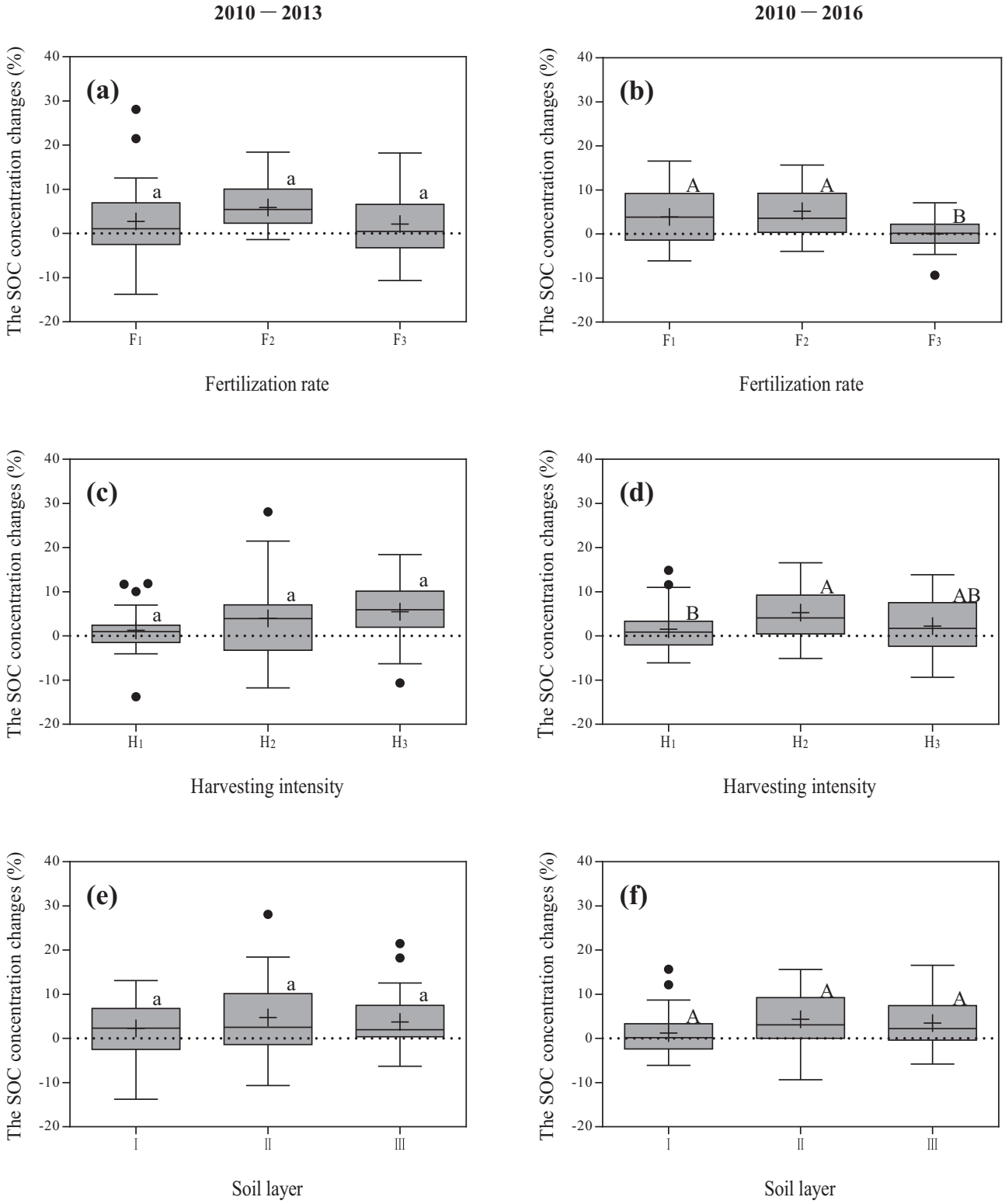

Fig. 4. Boxplots of SOC concentration change values (n = 27) under different fertilization rates, harvesting intensities, and soil layers in 2010–2013 and 2010–2016. Circles mark outliers (1.5 to 3 box lengths from the box edge). +: mean value; F_1: high fertilization; F_2: medium fertilization; F_3: no fertilization; H_1: high intensity harvesting; H_2: medium intensity harvesting; H_3: low intensity harvesting; I: 0–10 cm soil depth; II: 10–30 cm soil depth; III: 30–50 cm soil depth. Different lowercase letters above the boxes indicate significant differences among different levels for the SOC concentration changes from 2010 to 2013 at $P < 0.05$; different capital letters above the boxes indicate significant differences among different levels for the SOC concentration changes from 2010 to 2016 at $P < 0.05$.

fertilization, harvesting, and the fertilization × harvesting interaction had significant effects on SOC concentration changes, but not on C storage. Only the interaction between high fertilization and high intensity harvesting, which we called the intensive management model, caused a decrease in 0–50 cm soil C storage. For the optimized management model, high fertilization and medium intensity harvesting

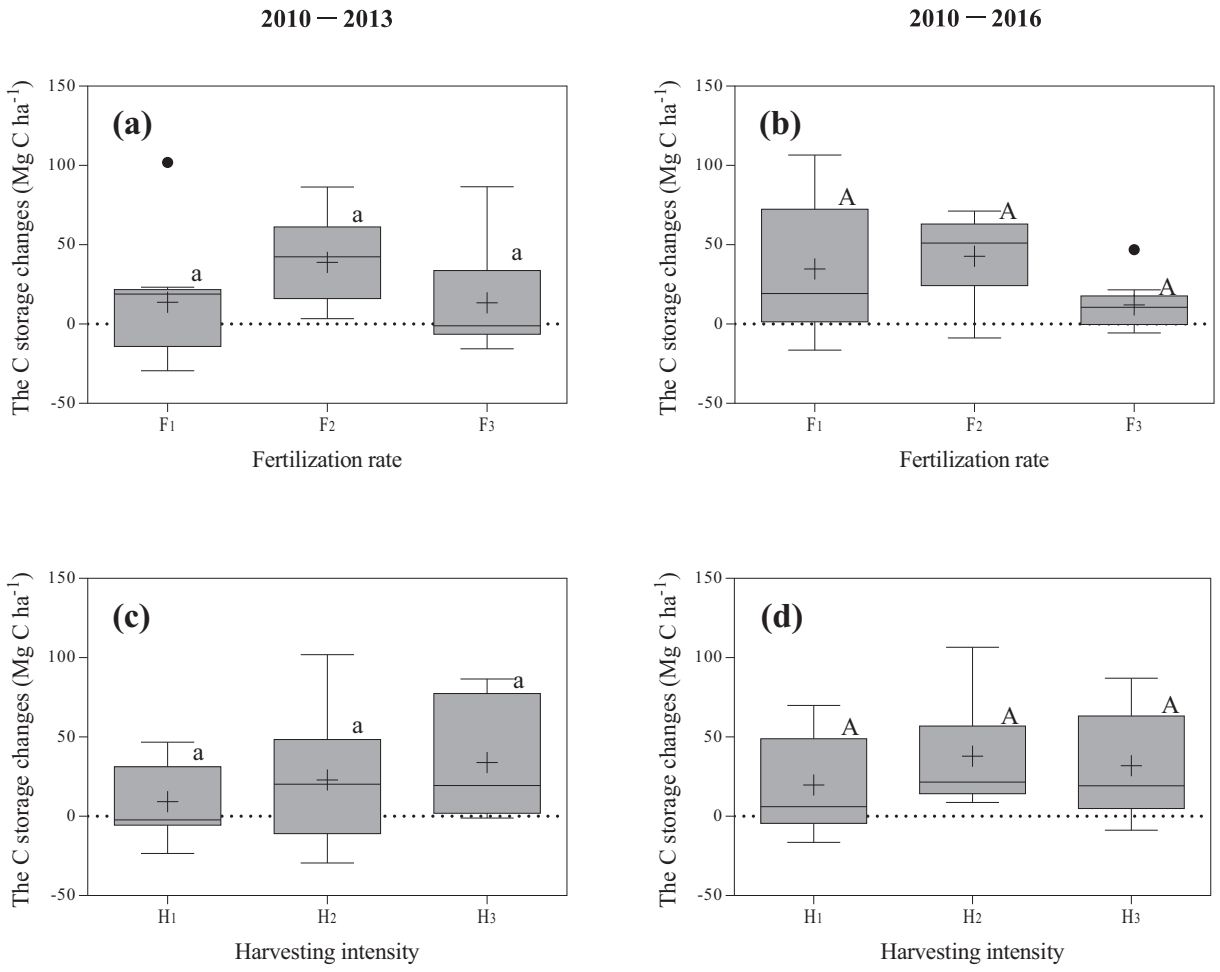

Fig. 5. Boxplots of C storage change values (n = 9) under different fertilization rates and harvesting intensities in 2010–2013 and 2010–2016. Circles mark outliers (1.5 to 3 box lengths from the box edge). +: mean value; F_1: high fertilization; F_2: medium fertilization; F_3: no fertilization; H_1: high intensity harvesting; H_2: medium intensity harvesting; H_3: low intensity harvesting. Different lowercase letters above the boxes indicate significant differences among different levels for the C storage changes from 2010 to 2013 at $P < 0.05$; different capital letters above the boxes indicate significant differences among different levels for the C storage changes from 2010 to 2016 at $P < 0.05$.

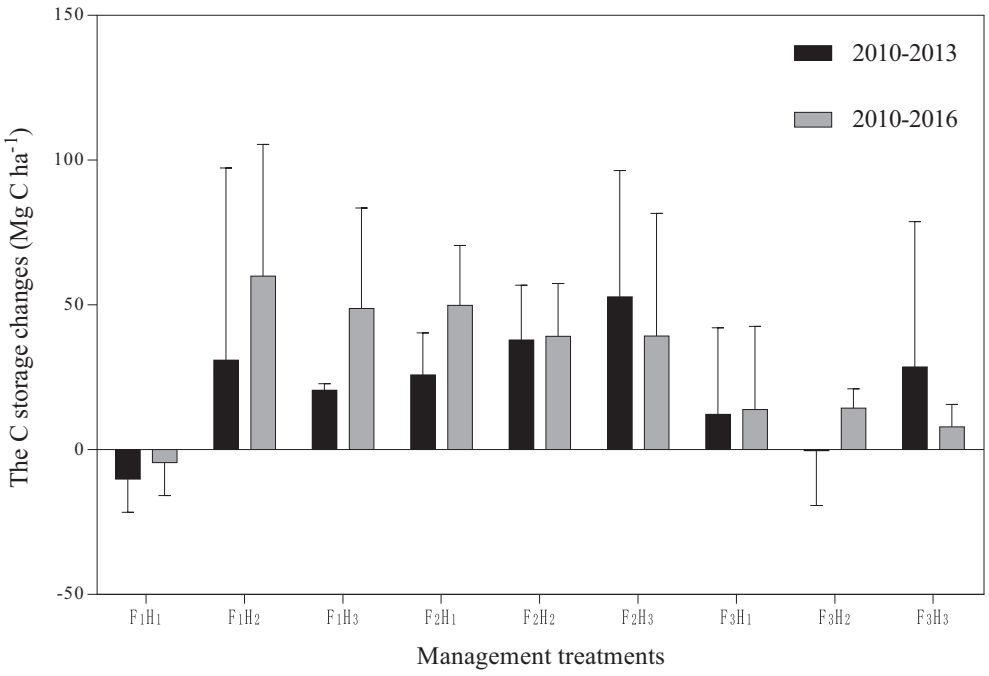

Fig. 6. The changes of C storage in the 0–50 cm soil depth under different management treatments in 2010–2013 and 2010–2016. F_1H_1: high fertilization and high intensity harvesting; F_1H_2: high fertilization and medium intensity harvesting; F_1H_3: high fertilization and low intensity harvesting; F_2H_1: medium fertilization and high intensity harvesting; F_2H_2: medium fertilization and medium intensity harvesting; F_2H_3: medium fertilization and low intensity harvesting; F_3H_1: no fertilization and high intensity harvesting; F_3H_2: no fertilization and medium intensity harvesting; F_3H_3: no fertilization and low intensity harvesting.

Table 2
Comparison of soil carbon stock in intensive and traditional management models between this study and other studies.

	Dangal et al., 2017	Li et al., 2013	This study
Country	Nepal	China	China
Soil depth (cm)	50	60	50
Forest type	Pine plantation	Moso bamboo plantation	Moso bamboo plantation
Intensive (Mg C ha^{-1})	78.65	80.84	47.62
Traditional (Mg C ha^{-1})	75.96	111.58	61.35
Optimized (Mg C ha^{-1})			112.15

increased soil C storage in the 0–50 cm soil layer the most, by 59.94 Mg C ha^{-1}.

Individually, for fertilization, the SOC concentration increased the most under medium fertilization, and for harvesting, the SOC concentration at low intensity harvesting increased the most in the first three years of management, while the greatest SOC increase occurred at medium intensity harvesting after six years of management.

In addition, our study indicated that the 0–50 cm soil carbon stock was 112.15 Mg C ha^{-1} under the optimized management model, which is 2.36 times larger than under the intensive management model, and 1.86 times larger than under the traditional management model. Thus, it is important to look at the changes in the total soil C stock if one of the major goals of forest management is to sequester carbon, and thereby mitigate global warming under REDD+ forest carbon sequestration mechanisms. At the same time, it is important to re-evaluate the carbon sequestration potential in Moso bamboo forest under the optimized management model.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.catena.2018.05.031.

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